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High Efficiency Transmit Antenna

Field of the Invention

The present invention relates generally to radio
5 communication systems and, in particular, to built-in active
integrated antennas incorporated into portable communication
devices.

Background

10 Portable communication devices, such as mobile
telephone handsets and pagers, are operated in an
environment that is power limited. Thus it is important for
these devices to be power efficient. To that effect it is
well known that most of the power dissipation occurs in the
15 power amplifier used for transmission. Furthermore there is
a commercial demand to reduce the size and profile of the
portable communication devices.

The power amplifier used by a portable
communication device is typically connected to an antenna by
20 a network of lumped passive electrical elements, such as
capacitors, resistors and inductors. The network of lumped
passive electrical elements is referred to as the output-
matching network. The network is used to provide an
impedance match between the power amplifier and the antenna.
25 However, the network typically restricts the operating
bandwidth of the power amplifier to a narrow band of
frequencies. This restriction leads to power amplifier
designs that are inherently narrow-band and specific to
certain types of applications.

30 Therefore it would be a desirable to enable a
direct connection between the power amplifier and the
antenna that increases the power-added efficiency of the

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power amplifier, eliminates the lumped passive electrical elements and reduces the size and profile of the antenna.

The prior art describes using the active integrated antenna approach, whereby active devices, such as

5   amplifiers and mixers, are directly connected to an antenna to minimize circuit size and increase the power-added efficiency of the active device. By adopting this approach there are a number of requirements that must be met by the design of the antenna for the resulting circuit to be

10 operable. For example, once combined with a power amplifier, in addition to its original role as a radiating element, the antenna must also serve as a power-combiner and harmonically tuned load.

From hereinafter the antenna will be referred to

15 as the radiating element, as now the power amplifier and radiating element together serve as an active antenna.

The typical load impedance for a power amplifier ranges between 10-25 Ω. By directly connecting the output terminal of the power amplifier to the radiating element, an

20 output-matching network is eliminated. Thus the amplifier design is simplified because the classical 50 Ω termination, realized by a network of lumped passive electrical elements, is not required. Furthermore, since there is no longer a need for lumped passive electrical elements connected to the

25 output of the power amplifier, chosen for specific frequencies, the power amplifier itself becomes broadband.

Although there is some mismatch loss between the power amplifier and the radiating element, it is tolerated by tuning the radiating element to provide a class-F or

30 inverse class-F load directly to the amplifier for high-efficiency and high-power operation.

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To further elaborate on the efficiency problem, a signal upon entering a power amplifier is typically free of distortion. However, due to the typically non-linear operation of a power amplifier, distortion of the signal

5   occurs within the power amplifier. The distortion manifests itself as harmonics of the fundamental (carrier) frequency f_0 of the signal that can be easily identified in the frequency domain. The second ($2f_0$) and third harmonics ($3f_0$) of the fundamental frequency f_0 of a signal typically consume the

10   most power of all the harmonics generated; thus, these two harmonics are of primary concern as they lead to the largest reductions in power added efficiency within the power amplifier.

However the presence of harmonic frequency

15   components alone do not lead to the greatest reductions of the power added efficiency of a power amplifier. It is only when the harmonic voltages and currents are substantially in phase with one another within the power amplifier resulting in heat dissipation will the power added

20   efficiency of the power amplifier suffer substantial reductions. Furthermore it should be noted that at low input power levels there is little or no harmonic energy but the efficiency is typically quite low. This is due to the fact that the energy dissipated within the power amplifier

25   is typically quite high.

Class-F and inverse class-F load impedances can be used to provide impedance matching at the output of a power amplifier. The class-F load provides an optimum power match for the power amplifier at the operating frequency f_0, a

30   short circuit at the second harmonic $2f_0$ and an open circuit at the third harmonic $3f_0$. The inverse class-F load provides an optimum power match for the power amplifier at the operating frequency f_0, an open circuit at the second

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harmonic $2f_0$ and a short circuit at the third harmonic $3f_0$.
Inherently these classes of impedances provide the desired
harmonic loading for a power amplifier to reduce the amount
of power transferred to the transmission of the second and
5 third harmonics, thus raising the efficiency of the power
amplifier. The short circuits and open circuits for the
harmonics at the load cause the voltages and currents to be
reflected away from the load. By generating harmonics and
then reflecting them back from the load creates a situation
10 where the voltage and currents at the output of the power
amplifier are sufficiently out of phase, such that the power
dissipation is minimized by effectively minimizing the
overlap of voltages and currents of the harmonics.

Among the antennas that can facilitate this type
15 of design, the planar inverted-F antenna (PIFA) is one of
the most promising. The planar inverted-F antenna can be
tuned to provide both class-F and inverse class-F load
impedances. The planar inverted-F antenna serving as the
radiating element also provides an attractive radiation
20 pattern that provides a null towards the user, thus reducing
potential biological interaction, and has a cross
polarization pattern that is desirable for the urban
multipath environment.

A planar inverted-F antenna of the prior art
25 consists of a planar radiating element, a feed pin, a ground
plane and a shorting plate of narrower width than that of
the shortened side of the planar radiating element. The
degree of freedom used to design and tune planar inverted-F
antennas is the width of the short circuit plate. As such
30 the prior art lacks features that make it flexibly tunable.
In particular, the prior art is characterized by a
difficulty in utilizing the classic rectangular planar
inverted-F antenna structure, having only a single narrow

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shorting plate, to realize class-F and inverse class-F impedances over a wide range of real input impedances.

Summary of the Invention

5   The present invention overcomes the above-identified deficiencies in the art by providing a low-profile, scalable radiating element which enables the power amplifier to be operable at a plurality of frequency bands, thus making the power amplifier effectively broadband.

10   Furthermore, this invention relates to the tuning of planar radiating elements that may be used to provide optimal impedance matching between a power amplifier and free space, so that the power-added efficiency of the power amplifier is substantially increased.

15   An aspect of the invention is to provide a symmetrical planar radiating element structure defined by at least one line of symmetry along the planar radiating element surface and a method of tuning said symmetrical planar radiating element structure to realize either a

20   class-F or inverse class-F load impedance, such that the input terminal of the radiating element can be directly connected to the output terminal of a power amplifier via a length of transmission line.

Another aspect of this invention is to provide a

25   structure and method of tuning a rectangular planar radiating element to realize either a class-F or inverse class-F load impedance, such that the input terminal of the radiating element can be directly connected to the output terminal of a power amplifier via a length of transmission

30   line.

The present invention also provides a means for harmonic tuning of the output of the power amplifier, in

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addition to providing either class-F or inverse class-F load
impedances.

More specifically, the present invention provides
a structure of an active planar inverted-F antenna that
5 makes use of two shorting pins and a feed pin to realize
inverse class-F impedances and to provide harmonic tuning
for a power amplifier. This invention provides a planar
inverted-F antenna structure that can realize class-F and
inverse class-F impedances over a wide range of real input
10 impedances. The elements of the invention combine with
classic planar inverted-F antenna structure to provide a
radiating element that can be tuned to realize class-F and
inverse class-F impedances over a wide range of real input
impedances. The second shorting pin allows the response of
15 the radiating element to be tuned at the second and third
harmonic. The short section of transmission line allows
further fine-tuning at the fundamental frequency and its
harmonics.

Yet another aspect of the invention is to provide
20 a method of tuning a planar inverted-F antenna, for either
class-F or inverse class-F impedances, to provide optimal
matching at a single frequency.

Yet another aspect of the present invention is to
provide a method of tuning the planar inverted-F antenna to
25 operate at different transmission frequencies once it has
been optimized for a single transmission frequency.

The invention utilizes two shorting pins, instead
of a single shorting plate, connected between the top plate
and the ground plane to tune the radiating element to either
30 class-F or inverse class-F impedances over a wide range of
frequencies. In doing so, the present invention also
provides for a radiating element with co-polarized

electromagnetic field components and cross-polarized electromagnetic field components.

Another aspect of the invention is to provide a method of tuning an offset top loaded monopole, for inverse
5   class-F impedances, to provide optimal matching at a single frequency.

Yet another aspect of the present invention is to provide a method of tuning the offset top loaded monopole to operate at different transmission frequencies once it has
10   been optimized for a single transmission frequency.

Other aspects and features of the present invention will become apparent, to those ordinarily skilled in the art, upon review of the following description of the specific embodiments of the invention.
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Brief Description of the Drawings

Figure 1a is a schematic of the side view of a Planar inverted-F Antenna (PIFA) of the present invention;

Figure 1b is a schematic of the top view of the
20   PIFA, of Figure 1a;

Figure 2 is a schematic of the equivalent circuit model of the PIFA in Figures 1a and 1b;

Figure 3a is a schematic of the top view of a PIFA optimized to provide a class-F impedance load;

25   Figure 3b is a schematic of the side view of the PIFA of Figure 3a;

Figure 4a is a schematic of the top view of an offset top-loaded monopole (TLM) optimized to provide an inverse class-F impedance;

30   Figure 4b is a schematic of the side view of the offset-TLM of Figure 4a.

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Description of the Preferred Embodiments

Figures 1a and 1b illustrate schematic views of one embodiment of the invention. The planar inverted-F antenna serves as a radiating element comprising a top plate

5 10 a dielectric substance 15 with a dielectric constant (i.e. relative permittivity) ε_r, and a ground plane 11. The dielectric substance is a height h, where by the height defines the height of the planar inverted-F antenna. The ground plane 11 extends beyond the edges of the top plate to

10 the extent that its electromagnetic characteristics allow it to be approximated as a ground plane that has infinite length and width. As such, the electromagnetic edge effects associated with a finite dimension ground plane can be ignored in the design process.

15 A feed pin 20 is connected to the underside of the top plate 10. A first shorting pin 21 and a second shorting pin 22 (not shown in Figure 1a) are connected between the underside of the top plate 10 and the ground plane 11, such that an imaginary line between the feed pin 20 and shorting

20 pins 21 and 22 forms a right angle whose sides are parallel to two respective sides the top plate 10. In Figure 1b it can be seen that the shorting pins, 21 and 22, are a distance ρ_1 and ρ_2 from the feed pin 20. Preferably the distances ρ_1 and ρ_2 are equal.

25 Feed pin 20 is connected between the top plate 10 and a short length of transmission line 30 having characteristic impedance Z_0 and length 1. Transmission line 30 is used to fine-tune the input impedance of the radiating element for class-F and inverse class-F operation.

30 The equivalent circuit model, shown in Figure 2, allows one to model the operation of the planar inverted-F antenna having two shorting pins in a manner similar to that

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of a folded monopole type antenna. The difference being a
greatly reduced foot print (i.e. Area occupied by the
radiating element) and the option for wide ranges of tuning.
The radiating element (antenna) mode is excited such that
5   the feed pin 20 and the shorting pins 21 and 22 are driven
in phase similar to the operation of a top-loaded monopole.
A transverse mode is also excited such that currents between
the feed pin 20 and the shorting pins 21 and 22 are out of
phase and behave as shorted sections of transmission line.
10   The inclusion of the second pin results in a second
radiating element mode and a second transmission line mode.
An inductor L1 and a second inductor L2 represent the shunt
inductances due to the shorted transmission line modes. A
transformer 40 and a second transformer 43 have turns ratios
15   (1+a) and (1+b), respectively, that represent the current
coupling between the feed pin 20 and the two shorting pins
21 and 22 for radiating element electromagnetic modes. A
series RC circuit 41 and a second series RC circuit 42
represent the impedance of two top-loaded monopoles,
20   respectively.

　　　　With reference to Figure 1b the top plate 10 has
dimensions of length L and width W. If the planar inverted-
F antenna is designed as an optimum load at frequency f_0,
then it is easily converted to operate at another frequency
25   f_1 by scaling all of the aforementioned dimensions according
to the following relations:

$$1)\quad h' = h\frac{f_0}{f_1}$$

$$2)\quad L' = L\frac{f_0}{f_1}$$

$$3)\quad W' = W\frac{f_0}{f_1}$$

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$$4) \quad \rho' = \rho \frac{f_0}{f_1}$$

$$5) \quad l' = l \frac{f_0}{f_1}$$

In general, a method of tuning a planar inverted-F antenna with two shorting pins to realize a class-F
5   impedance comprise the following steps:

1.a.) Varying the top plate position so that the feed pin 20 is located substantially near the center to provide a nearly class-F impedance at the frequency f_0. An additional effect of placing the top plate such that the
10   feed pin 20 and shorting pins 21 and 22 are closer to the center of the top plate (zero-offset) is a greater bandwidth available for transmission of a signal.

2) Increasing or decreasing the distance ρ between the shorting pins 21 and 22 and the feed pin 20, to
15   respectively increase or decrease the real part of the input impedance Z_{in} of the planar inverted-F antenna. Thus the distance ρ is chosen to increase or decrease the input impedance Z_{in} as required. It should also be noted that apart from the circular radiation pattern typical for
20   vertically polarized antennas, the E_ϕ field in the overhead position at position $\theta = 0$ increases as ρ increases. Also as ρ increases, the real part of the driving point impedance also increases for most frequencies. However, increasing ρ also has the effect of increasing the resonant frequency of
25   a characteristic impedance loop that can be seen on a Smith Chart (not shown).

3) Increasing or decreasing the height h of the top plate 10 above the ground plane 11 to respectively increase or decrease the real part of the planar inverted-F
30   antenna's input impedance Z_{in} at f_0, and also respectively

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reduce or increase the reactance (i.e. The imaginary part) of the planar inverted-F antenna's input impedance Z_{in}.

4) Adjusting the length l of the transmission line 30 to fine-tune the input impedance Z_{in} of the planar

5   inverted-F antenna. The short section of transmission line 30 can be used to fine-tune the input impedance at the operating frequency and maintain the desired harmonic loading at the second and third harmonics. To realize an inverse class-F load usually requires between 25% to 50%

10   more transmission line length at the input to the planar inverted-F antenna than for the class-F load.

In the alternative the planar inverted-F antenna may be tuned to realize an inverse class-F impedance by replacing step 1.a.), from above, with 1.b.) as stated

15   below:

1.b.) Varying the top plate position so that the feed pin 20 is located substantially close to a corner of the top plate 10 to provide a nearly inverse class-F impedance at a frequency f_0. In this case the E_ϕ field

20   component (the electric field component in the azimuth direction relative to a perpendicular line from the surface of the radiating element) in the overhead direction is a maximum for the case of maximum offset where the feed pin 20 and shorting pins 21 and 22 are located a maximum distance

25   from the center of the plate.

In conjunction with the tuning steps above choosing a type of dielectric material to be placed between the top plate 10 and ground plane 11 is also an optional design consideration. The type of dielectric used between

30   the top plate and ground plane can reduce the required area for the top plate. Materials with higher dielectric constants, relative to free space, will reduce the area

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relative to the area required if free space is the
dielectric substance. Materials with lower dielectric
constants will have the opposite effect. The type of
dielectric substance is also chosen specifically for the
5   range of frequencies where it may be effective. Therefore,
the dielectric substance is chosen considering the frequency
of operation and constraints on the size of the radiating
element.

          Examples of the types of dielectric material that
10   can be used are alumina, quartz, polytetra fluoroethylene,
epoxy/glass and air. Preferably, alumina or quartz or
polytetra fluoroethylene is used when the operating
frequency is above 1GHz. Preferably, epoxy/glass is used
when the operating frequency is below 1GHz. Other suitable
15   dielectric materials for different applications would be
obvious to those ordinarily skilled in the art.

          Upon tuning the radiating element to operate at a
frequency f_0, the radiating element can be scaled, as
described above, to change the operating frequency of the
20   radiating element to a new operating frequency f_1.

          Figure 3a is an illustration if the top view of
the planar inverted-F antenna optimized for an input-
impedance that is considered class-F at an operating
frequency of $f_0 = 2.7$GHz. The feed pin 20 is located at a
25   central location within the perimeter of the top plate.
Figure 3b is a schematic of the side view of the same planar
inverted-F antenna.

          With reference to Figure 3a, the height h of the
planar inverted-F 10 is 3.175mm and the top plate is square
30   with dimensions L x W being 25.4 mm x 25.4 mm. Each
shorting pin 21 and 22 is located a distance $\rho = 7.62$ mm
placed so that they form a right angle with the feed pin 20

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which is slightly offset from the center of the top plate. As per an assumption made earlier the ground plane extends past the edges of the top plate to approximate a infinite ground plane, and in this embodiment the dimension of the

5 ground plane is 38.1 mm x 38.1 mm.

Referring to Figure 3b, it was found that for the planar inverted-F antenna to provide a precisely tuned class-F impedance at $f_0 = 2.7GHz$ it had to be connected in series with the transmission line 30 having a length of 14

10 mm, a dielectric constant of 2.2 and above a substrate 0.381 mm thick. That is, the transmission line is above a different dielectric material (not shown) serving as a substrate with dielectric constant $\varepsilon_r = 2.2$, a thickness of 0.381 mm and metalized on the side opposite the transmission

15 line (e.g. microstrip line). This arrangement is shown in Figure 3b; and in reference to Figure 3b, the planar inverted-F antenna 10 will have a class-F response when it is measured at terminal 60.

If, for example, it is required that the PIFA of

20 Figures 3a and 3b must have its operating frequency be tuned to say $f_1 = 1.8GHz$ (a new operating frequency), then the scaling equations provided above would result in a new PIFA with the following dimensions: h = 4.763 mm; L = 38.1 mm; W = 38.1 mm; ρ = 11.43; Length of transmission line = 21 mm.

25 Note that the dielectric material between the top plate and the ground plane of both planar inverted-F antennas must be the same for the scaling according to the invention to work as intended.

The embodiment of the invention described in

30 detail thus far was implemented using a rectangular top plate and two shorting pins placed around a feed pin to form a right angle. The imaginary lines of the right angle were

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parallel and perpendicular to respective sides of the rectangular top plate. However, the present invention is not limited to embodiments having a rectangular top plate or embodiments where the feed pin and the shorting pins form a

5 right angle or substantially a right angle.

Any symmetric top plate defined by at least one line of symmetry across its broadest surface could be used in place of the rectangular top plate described above.

Furthermore, the two shorting pins need only be

10 placed around the feed pin such that the distance to the feed pin from either shorting pin is substantially equal. In the embodiment described above it was found to be preferable to place the shorting pins around the feed pin such that a right angle was formed. Possibly, if the angle was greater

15 than ninety degrees, the shorting pin spacing increase would possibly improve the bandwidth or the tunability of the radiating element. This may degrade the radiation pattern however, possibly decreasing the pattern in the overhead direction. Decreasing the pin angle would result in the

20 shorting pins being closer and thus lowering the bandwidth of the radiating element.

Additionally, the imaginary lines of the angle formed by the shorting pins and feed pin would not necessarily have to be placed in any particular orientation

25 in relation to the edges of the top plate. In the embodiment described above it was found to be preferable to have imaginary lines of the right angle formed by the shorting pins and feed pin be parallel and perpendicular to the edges of the rectangular top plate.

30 Another embodiment in accordance with the aspects of the invention is an offset top-loaded monopole tuned to provide an inverse class-F impedance. A top-loaded monopole is essentially a short monopole with a flat top plate.

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Thus, conceptually, a top-loaded monopole is obtained if shorting pins 21 and 22 are removed from the planar inverted-F antenna illustrated in Figures 1a and 1b.

The top-loaded monopole can be optimized for
5   inverse class-F operation. However, the drawbacks of doing so are that the top plate must be much larger and a longer length of transmission line is required for the input impedance tuning. Additionally, the top-loaded monopole is limited, as it cannot be used to realize class-F impedances.
10   Despite these limitations, compared to the planar inverted-F antenna with two shorting pins, the top-loaded monopole can be tuned to realize inverse class-F impedances. In order to realize inverse class-F impedances the feed pin is offset from the center of the top plate so that is close
15   to a corner of the top plate. Thus, it is a maximal distance away from the center. Accordingly, from herein, the top-loaded monopole used to realize inverse class-F impedances will be referred to as the offset top-loaded monopole.
20   For the top-loaded monopole, feeding the top plate closer to the edge results in a wider bandwidth as well as greater cross-polarization contribution in the overhead direction. This is the same phenomenon present in the planar inverted-F antenna with two shorting pins. For the
25   case of a center-fed top-loaded monopole, there is no cross- or horizontally-polarized field at zero elevation above the surface of the radiating element. Offsetting the feed-pin, results in an asymmetric current distribution on the top plate resulting in the E_ϕ field component in the top
30   direction.

Figures 4a and 4b illustrate the top view and side view of the offset TLM optimized to operate at 2.2GHz

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respectively. A top plate 100 is placed at a height h over
a ground plane. The dimensions of the top plate are 55.88
mm x 55.88 mm, and the required length of transmission line
used to fine tune the offset-TLM is 25 mm. There are no
5   shorting pins and only a single feed pin 200. The lack of
the shorting pins causes significant increases in the area
of the top plate and length of the transmission line. Note
that the fed pin 200 is near the corner of the top plate so
that the input impedance to this radiating element is
10 approximately that of an inverse class-F impedance.

        The embodiment of the invention described in
detail thus far was implemented using a rectangular top
plate and a feed pin placed in substantially near a corner.
However, the present invention is not limited to embodiments
15 having a rectangular top plate or embodiments where the feed
pin in placed substantially near a corner of the top plate.

        Any symmetric top plate defined by at least one
line of symmetry across its broadest surface could be used
in place if the rectangular top plate described above.

20   Additionally the feed pin can be placed
substantially close to an edge of the top plate instead of
substantially close to a corner of the top plate. In the
embodiment described above it was found to be preferable to
have the feed pin substantially close to a corner.

25   In both configurations, the planar inverted-F
antenna and offset top-loaded monopole have a large co-
polarized electromagnetic field component in the azimuth
plane and a cross-polarized filed component in the elevation
plane. For each of the radiating element configurations,
30 scaling can be used to tune the radiating element to a
different frequency once the radiating element has been
designed for a first frequency of operation.

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The inverse class-F planar inverted-F antenna radiating structures are smaller than the corresponding offset top-loaded monopole structures. Additionally they both greatly simplified the power amplifier design by in
5 effect allowing a single power amplifier to be considered broadband by eliminating a lumped passive electrical element network between the power amplifier and the radiating element and simply scaling the radiating element for use at different frequencies.

10 For both the planar inverted-F antenna and offset top loaded monopole there may be instances where a low enough input impedance Z_{in} to the radiating element is sought such that the desired impedance can be obtained directly at the feed pin without the use of a transmission line. In this
15 case, the transmission line has zero length.

What has been described is merely illustrative of the application of the principles of the invention. Other arrangements and methods can be implemented by those skilled in the art without departing from the spirit and scope of
20 the present invention.